The MISR calibration program

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Abstract. The Multi- angle Imaging SpectroRadiometer (M I SR) is currentl y under development for N A S A ' s Ear th Observing System (EOS). The instrument consists of nine pushbroom cameras, each with four spectral bands in the visible and near - infrared, The cameras point in different view directions to provide. measurements from nadir to highly oblique view angles in the along-track plane. Multiple view-angle observations provide a unique resource for studies of clouds, aerosols, and the surface. In order to accomplish its scientific objectives, MISR is built to challenging radiometric and geometric performance specificat ions. Radiometric accuracy, for example, must be within ±3%/ 10 (over high reflecta nce, spatiall y uniform scenes) and polarizat ion insensitivity mist be better than ± 1%. An On-Board Calibr ator (OBC) supplements the preflight characterizations and]IIo\'ides monthly updates to the instrument gain coefficients. Spectralon diffuse panels are used within the OBC to provide. a uniform target for the. cameras to view. The absolute radiometric scale is established both preflight and in-orbit through the use of detector standards. 1)uring the mission, ground data processing to accomplish radiometric calibrat ion, geometric rectification and registration of the nine view-angle imagery, and geophysical retrievals will proceed in an automated fashion. A global data set is produced each nine days. This paper- details the preflight characterization of the MISR instrument, the. design of the OBC, and the radiance product processing. Detailed specification and test plans are given, in reference guide style, so as to allow subsequent publications io highlight specific design and test results.

1. INTRODUCTION

MISR will acquire systematic multi-angle imagery to monitor top - atmosphere and surface. reflectances on a global basis, and to characterize the. shortwave radiative. properties of aerosols, clouds, and surface scenes. Data from the MISR experiment will enable advances in a number of areas concerning global change:

- **Clouds.** High resolution bidirectional reflectances will be used in cloud classification, and the spatial and temporal variability of cloud hemispheric reflectance will be determined. Stereoscopic measurements Will be used to retrieve cloud-top elevations. These data will help discern the. role of different clouds types in the Earth's energy balance.
- **Aerosols.** Multi-angle radiance data will be used to determine aerosol optical depth, and to identify particle composition and size distribution. These data will enable a global study of the role of aerosols on the, energy budget, and will provide data used for atmospheric correct ion of surface imagery.
- **Land surface.** Atmospherical ly-corrected surface bidirectional reflectances will be used to estimate surface hemispheric reflectance, an important climate variable, anti to characterize vegetation canopy structures. These data wiii be important for investigating the effect of land surface processes cm climate.
- **Oceans.** MISR will provide data to support ocean biological productivity studies in regions of iow phytoplankton pigment concentrations, such as much of the tropical oceans.

2. INSTRUMENT

The MISR instrument, to be launched in 1998 as one of five instruments on the first Earth Observing System platform (EOS-AM), will fly in a 705 km (440 mile) sun-synchronous descending polar orbit, with an equatorial crossing time of 10:30 a.m. The instrument will be used to produce registered global data sets from nine cameras and fout spectral bands. The wavelength bands are nominal] y centered at 443, 555, 670, and 865 nm, with bandwidths varying between 15 and 25 nm. Data will be acquired with cross-track spatial sampling ranging from 275 m (250 m in the nadir) to 1.1 km (1.0 km in the nadir), depending on the "canma-configuration", or on-board pixel averaging mode. Data will typically be 4 x 4 pixel (cross. x along-track) averaged before transmission with selected channles operating without averaging. Additionally, specific "Local Mode" targets on the Earth will be observed with avei aging inhibited in all channels. Equal crosstrack instantaneous fie.lds-of-view (IFOV) for the off-nadir cameras is provided by having four lens designs, named A through D, differing in focal length so as to compensate for variations in distance to Earth. The cameras consist of a nadir camera (An) anti two banks of cameras pointing in the forward (Af, Bf, Cf, and Df) and aftward directions (Aa, Ba, Ca, and Da) with respect to the spacecraft ground track, Images are acquired at (he. Earth's surface. with view angles of 0°, 26,10, 4S.6°, 60.0°, and 70.5°, fore and aft of zenith. The instantaneous view directions for the 36 data channels arc depicted in Figure. 2-1, The actual camera boresight angles arc 0°, ±23.3°, f-40.0°, ±51.2°, and ±58.0° (where the plus or minus sign indicates fore or aft viewing, respectively). These angles differ from the view angles at the surface due to the curvature of the Earth. The instrument swath width (see Figure 2-1) provides global coverage every nine days at the equator (two days at the. poles).
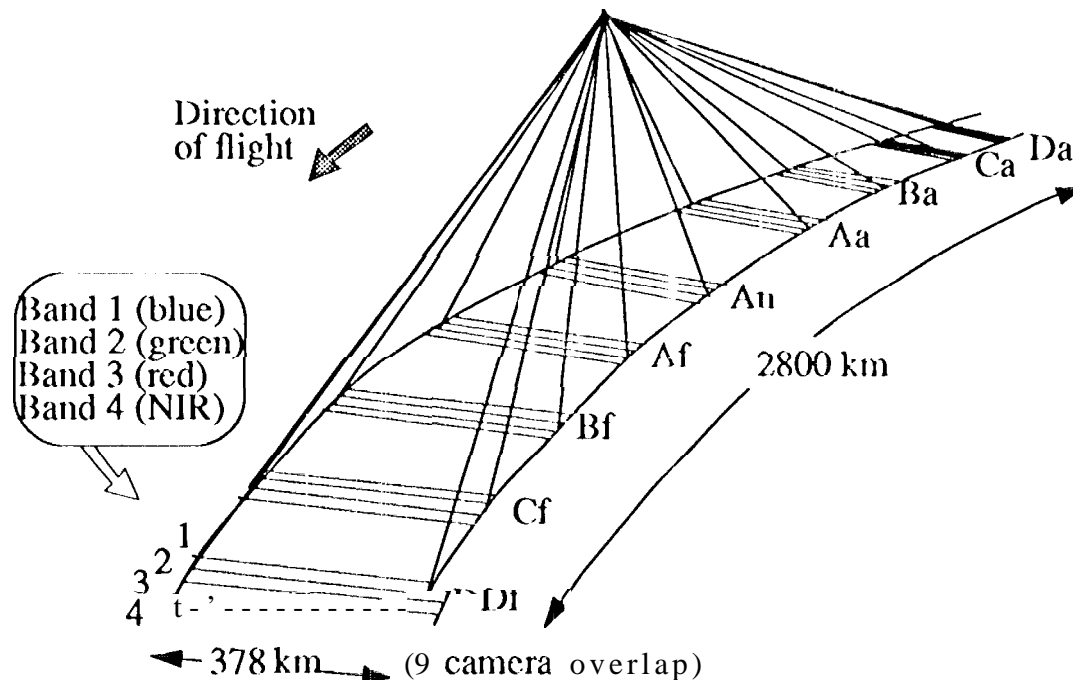

Figure 2-1. MISR camera projections 10 Earth.

2.1 Camera Design

Each camera uses four Charge-Coupled Device (CCD) line arrays per focal plane, 1504 photoactive pixels plus 16 light-shielded per array, with 2 lx 18 pm (O, 83x0,71 roil) pixels (cross-track by along-track). Each line array is filtered to provide one of four MISR spectral bands. The spectral profile is Gaussian in shape which, used in conjunction with a Lyot depolarizer, will allow the instrument to be polarization insensitive.

... is design, Each MISR camera consists of a lens barrel and a camera head which houses the focal plane structure and to which is attached the CCD driver electronics. The camera heads and electronics arc identical for all nine cameras, leading to a modular design in which only the. lens barrels are unique. "l'he first order properties of the. four unique lens designs are shown in Table 2-1.

Table 2-1, MISR optics first-order parameters

Camera Design	Effective Focal Length (mm)	Field of View	View angle at Earth's surface
A	59.3	±14.9°	;",2;."10 ""-
B	73.4	±12.1°	45.6°
C	95.3	±9.4°	60.0°
D	123.8	±7.3°	70.5°

Early in the. lens design phase selected cerium-doped, radiation-resistent glasses were tested along with more conventional lens materials. After testing, at several times the anticipated EOS charged particle dose, it was demonstrated that transmittance. losses at the MISR wavelengths were low (Al-Jumaily, 1992). These data demonstrated that conventional lens glasses could be used, thereby extending the number of glasses available to the. design. The final design is superachromat ic (having a common focus at three MI SR wavelengths) and thermal] y compensated for focus. It is a seven-element telecentric Biotar form. (In the telecentric design, the chief rays exit the cameras nearly parallel to the optical axis, independent of location in the field of view, with the benefit that bandpass of the focal plane interference filters is nearly constant across the field). An additional benefit of the telecentric design is that optical transmittance is only a weak function $(\cos^{-1}\theta)$ of field angle θ. in order to meet the system radiometric accuracy requirements, a double-plate Lyot depolarizer is also incorporated into each of the cameras in order to scramble the polarization state, The effectiveness of Lyot depolarizers is dependent on the spectral bandwidth as well as the spectral band shape. They are most effective for Gaussian-like band shapes. Thus, the MISR filters are specified to have Gaussian band shape profiles in order to optimize the performance of the Lyot depolarize.rs.

Within the lens barrel, the lenses are. mounted with a combination of aluminum and Rulon spacers with threaded aluminum retaining rings that clamp each lens/ spacer assembly. The thickness of the Rulon has been calculated to match the lens-Rulon coefficient of thermal expansion to the expansion of the aluminum housing. Thus the clamping force on the lens elements

remains constant during thermal excursions. The centering of the lenses is controlled by the aluminum spacers that have been machined to be tangent to the lens element surfaces. Proper clearances prevent squeezing the lenses (which could result in breakage) during thermal cycling to the coldest survival temperature.

Control of focus shift with temperature change is also provided using Rulon. The dominant factor affecting focus location for the cameras is the change of index of refraction of the glasses with temperature. Maintaining the. position of the detector plane so that it coincides with the shifting focal plane of the lens requires moving the. detector plane to follow the change in lens focus with temperature. The lenses were accurately modeled in CODE V and thermal excursions were simulated. The resulting thermal shift predictions were used to design a passive thermal compensation scheme. A cylinder of Rulon A was mounted between the detector housing and a fiberglass tube used to thermally isolate the detector. The length of the Rulon was calculated to move the detector plane the needed distance and direction to maintain focus. In order for this focus concept to work, the Rulon needs to be nearly the same temperature as the lenses. This is accomplished through the thermal blanketing around the camera, and through the high thermal conduction of the aluminum lens barrel and detector housing. Thermal gradients are calculated to be < 1°C.

Filters. The mosaic filter consists of four separate filter sticks epoxied into a single structure. When installed into the CCD package each of the four CCD line arrays sees a different color. The filters are centered on 441, 5S5, 670, and 866 nm, which differ slightly from the system bandpass specification such that when the optics and CC]) spectral responses are taken into account the system requirements are met, The MISR filter specifications require. a high degree of uniformity among all filters, as well as very stable and durable coatings which will not shift or degrade with age or environmental stresses. Ion assisted deposition (IAD) technology has therefore been utilized. Manufacturing the passband and blocking layers on separate substrates prevents cost from being prohibitive. After the coating runs the two substrates are bonded together, with the coatings to the interior. Optical masks are incorporated into the assembl y to prevent white-light leakage throught the inter-filter epoxy bonds. The completed filter is 650 pm (2S.6 mils) thick.

Detectors. The MISR CCD architecture consists of four line arrays on a common piece of silicon, with a spacing of 160 µm (6.3 roils) center-to-center. The silicon die is mounted in a ceramic package. The filter defining the four optical bandpasses is aligned with the CCDs, but displaced above the focal plane by 38 µm (1.5 roil). The package has a laser welded window, is back filled with argon, and hermetically sealed. The hermetic package prevents contamination of the filter and CCD elements, eliminates humidity, and improves stability. Integration time for each line array can be controlled independently. This allows for different integration times in different bandpasses in order to equalize radiometric performance and maximize. signal-to-noise ratio. The arrays are operated at 50 kilopixels per second with a 40.8 msec line repeat time to provide 275 m of along-track separation between successive lines.

The MISR CCD's have a "thin-poly" design, a new technology developed to increase the detectors' sensitivity to wavelengths shorter than 500 nm. The architecture is otherwise based on standard 3-phase, 3-poly, n-buried channel silicon detector technology. Additional processing is performed to create the thin-poly CCD. Specifically, the third poly deposition over the photogate (active pixel) region is etched down. This is followed by deposition of a thin fourth poly layer. This etching and deposition process is necessary to insure that the poly layer thinning occurs over the photogate region only, and to maintain continuous electrical contact throughout the entire line

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array. 'I'he thickness of the poly gate over the active pixels is about 400 Å, as compared to 2000 Å for conventional devices.

The detector is cooled to -10° C with a single-stage Thermo-Electric Cooler (l'EC). . Temperature stability is within ±0. 10 C, accomplished by computer control of a heater. The TEC is always on and small amounts of heat are added to conti 01 the temperature. The heat generated by the TEC is conducted through the optical bench to which the nine cameras are attached, and then radiated to space with a dedicated TEC radiator. Due to the mass of the optical bench, it remains thermally stable with less than 2° C spatial or temporal gradients throughout the orbit.
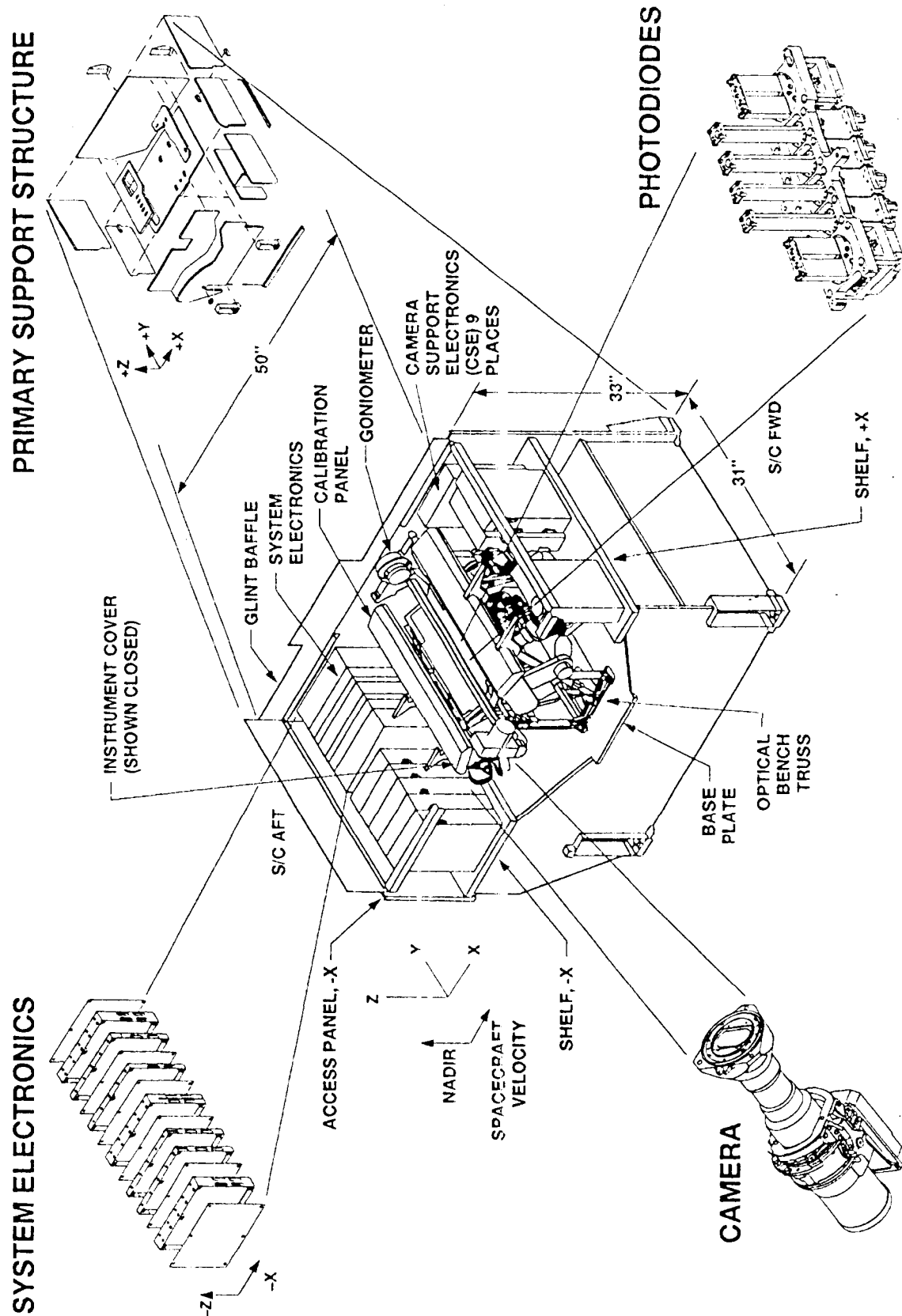
2.2 Instrument subsystems

Figure 2-2. Instrument subassemblies.

Structure. The cameras are mounted to the optical bench at their front (light entrance) end with the detector end cantilevered into the instrument cavity. Light baffles are mounted to the optical bench in front of each camera. The detector assembly is mounted to the end of the lens barrel. Attached to the detector assembly is a small, low-powered electronics box that provides static charge protection to the detector, carries the temperature. monitoring signals, and provides initial signal amplification. Thermal blanketing surrounds each camera to prevent thermal coupling between the cameras and the electronics inside the instrument cavity. The cameras are thermally tied to the optical bench. Each camera is designed to operate within the range of 0° C to 10° C.

As shown in Figure 2-2, the optical bench assembly is connected to the instrument structure with a system of titanium tubular bipeds. To ease. structul al and thermal loads on the optical bench and supporting bipeds the design separates the camera support electronics from the camera head. The camera support electronics will be mounted on a then-nally isolated structural platform. This platform will have thermal straps to conduct heat to a set of passive radiators. Each electronic box has a short cable that attaches to the respective camera head. The optical bench with attached optics will be thoroughly blanketed to protect it from internal heat radiation, The Primary Support Structure is designed to maintain rigid support for the optical bench and provides kinematic attachment to the spacecraft. In addition, it provides a structural mount for the passive radiators located on the nadir-facing side of the instrument, houses the instrument system electronics and the flight computers, and incorporates optical baffles to keep specular glints from neighboring instruments from illuminating MISR's optical calibration surfaces.

Figure 2-2

PRIMARY SUPPORT STRUCTURE

PHOTODIODES

SYSTEM ELECTRONICS

CAMERA

INSTRUMENT COVER (SHOWN CLOSED)

GLINT BAFFLE

SYSTEM ELECTRONICS

CALIBRATION PANEL

GONIOMETER

CAMERA SUPPORT ELECTRONICS (CSE) 9 PLACES

S/C FWD

SHELF, +X

S/C AFT

ACCESS PANEL, -X

BASE PLATE

OPTICAL BENCH TRUSS

SHELF, -X

NADIR

SPACECRAFT VELOCITY

50"

33"

31"

+Z
+Y
+X

Y
Z
X

-Z
-X

Electronics. The MISR electronics fall into three general areas: camera electronics, system electronics, and calibration electronics. Each camera is relatively autonomous with its own power supply and serial data interfaces. The power supplies are 25 kHz sine wave supplies, which provide high efficiency with simultaneous low noise performance. The camera electronics can stand alone through most testing and camera calibration. The design insures that if an in-flight failure occurs in a camera's electronics it is not allowed to propagate to another camera or to the system electronics. The camera digital electronics provide interfaces to the system electronics controlling the camera as well as all the drive and timing signals to the CCD focal plane, the double correlated signal chain, and engineering signal conditioning (ESC) circuits. The signal chain amplifies and converts the CCD video into 14 bit digital numbers. There are four signal chains per focal plane for a total of 36 in the instrument. The signal chains are hybrids, providing both noise and mass advantages. All camera digital circuits reside on Field Programmable Gate Arrays (FPGA's). This technology allows for increased packing densities and the speed of custom Application Specific Integrated Circuits (ASIC's) with the programming ease of Programmable Read-Only Memories (PROM's).

The system digital electronics' main function is to interface the instrument to the platform. All system electronics is redundant such that a single point failure can occur and the instrument will continue to function. The system electronics contains redundant 1750A computers with 1553-bus interfaces to the spacecraft. All commands from the spacecraft and engineering data go through the 1553-bus. The system electronics also provide the high speed data interface, control inputs to the cameras, control power throughout the instrument, and control all of the mechanisms. A system ESC circuit measures system-wide temperatures and voltages. All nine TEC'S (one for each camera) are powered by the system power supply and placed in series. A diode is placed in parallel with each TEC such that a single TEC failure does not disable the entire string. As in the cameras, all of the custom digital circuits will reside on FPGA's. System electronics provide the data averaging, as well as square-root encoding of the camera digital data streams. The latter processes reduce data volume loads to the spacecraft.

The calibration electronics consists of the calibration diode pre-amplifiers and the ESC circuits associated with the diodes, The pre-amps are the trans-conductance type operating in the picoamp region. The calibration diodes have their own ESC circuits since all cameras may not be on during instrument calibration, due to power constraints.

2.3 On-Board Calibrator

For both the preflight and in-flight calibrations MIS R output are radiometrically calibrated using a spatially uniform source whose radiant output is determined using detector standards. Source standards rely on a series of radiometric comparisons from the National Institute of Standards and Technology (NIST), through a lamp vendor, and to the instrument flat-field calibration source. Conversely, detector standards are based upon manufacturing knowledge of photon to electron conversion efficiency, filter transmittance, and acceptance cone of illumination. It is believed that the MISR detector standards provide greater radiometric accuracy than would be obtained using source standards, Preflight, an integrating sphere and laboratory photodiode standards are utilized. In-flight, MISR is calibrated using an On-Board Calibrator (OBC) that consists of two Spectralon diffuse calibration panels, High Quantum Efficiency (HQE) diodes in a trapped configuration, and single (not trapped) radiation-resistant PIN diodes, including one

mounted to a goniometer arm to provide angular characterization of the diffuse panels. Figure 2-3 shows the location of these elements with respect to the optical bench structure.
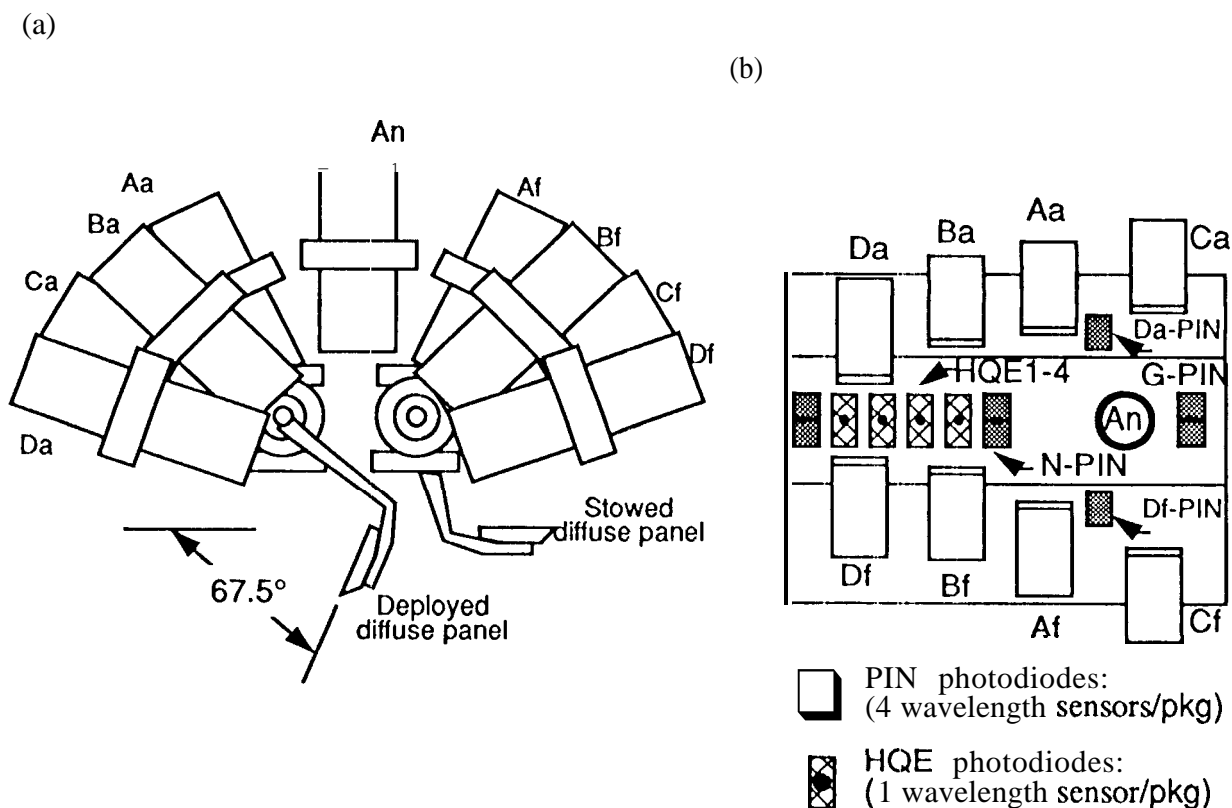
(a)

(b)

Figure 2-3. Location of a) the calibration panels and b) photodiodes on the optical bench.

At approximately monthly time intervals the panels are deployed for calibration. Over the North Pole, one panel will swing aftward to reflect diffuse sunlight into the fields-of-view of the aftward-looking and nadir cameras. Over the South Pole, the other panel will swing forward for calibration of the forward-looking and nadir cameras. Thus, the nadir camera will provide a link between the two sets of observations. By monitoring the panels with photodiode assemblies, and through consistency checks using overflight campaign data, slow changes in panel reflectance are allowable without compromising the calibration accuracy, since the photodiodes provide the primary standard.

The time available for calibration will be about seven minutes at each pole. In this time the cameras will see a range of illumination, due to sunrise (sunset at the South Pole) onto the panel, view of the Sun through a varying amount of Earth atmosphere (including atmosphere-free space). By using the photodiodes to measure the panel-reflected radiances, the cameras can be calibrated using data covering the dynamic range of the sensor. In addition to these panel views, the cameras will gather data over the dark Earth for three minutes each month. The dark-Earth data will establish the dark current spatial variability across the array. Dark current is expected to be slowly varying during the mission, gradually increasing due to particle radiation exposure.

Diffuse panels. The panels are required to be have a high, near-Lambertian reflectance. These properties are needed to direct sufficient energy into the cameras to reach the upper end of the sensor dynamic range. The Lambertian property also facilitates knowledge of the radiance into the cameras, as the radiance is measured by photodiodes at a particular panel view angle, and corrected for departure from Lambertian behavior. One challenging panel requirement is for uniformity in the reflected radiance field. This is necessary in order to accurately measure pixel-to-pixel and camera-to-camera differences in responsivity. To fulfill this requirement scattering within the instrument is minimized, and baffles are provided to block the panels from a view of other instrument and spacecraft structures.

After a materials search, SpectraIon has been selected as the material of choice for the MISR in-orbit calibration targets. Spectralon is a product of Labsphere (North Sutton, New Hampshire), and is composed of pure polytetrafluoroethylene (PTFE, or Teflon) polymer resin that is compressed into a hard porous white material using temperature and pressure sintering. No binders are used in the procedure. Spectralon is widely used in laboratory and **ground/** field operations as a reflectance standard. MISR has provided for the flight qualification of this material (Bruegge, et. al, 1993; Stiegman, et al., 1993). Areas of investigation for flight qualification include static-charge build-up studies, optical characterization, environmental exposure (including UV, humidity, atomic oxygen and thermal cycling impact studies), measurement of mechanical properties such as tension and compression strengths, and vibration testing. The diffuse panels are stowed and protected while not in use, Cumulative space exposure time (deploy time) for each panel is expected to be less than 100 hours over the mission life. With these factors panel stability is expected to be high (changing less than 2% the first year, and 0.5% per year thereafter).

Deployment of the panels, as well as the cover, will be actuated through the use of a mini-dual drive actuator (MDDA), providing redundancy and fault tolerance. A single motor is used for the goniometer. Redundancy is not implemented for the goniometer, since its failure would not be mission critical.

Calibration photodiodes. The diffuse calibration targets will be monitored by three types of diodes: radiation-resistant PIN photodiodes and two types of High Quantum Efficiency (HQE) diodes. (Note: "PIN" is a description of the diode architecture where p, intrinsic, and n doped layers are stacked.) The radiation-resistant photodiodes will be fabricated four to a package, each diode filtered to a different MISR spectral band. The fields-of-view are approximately 7°, sufficient to allow the required signal-to-noise ratio (SNR) of 500 to be achieved. Five such packages will be used. Two will view in the nadir direction, two in the Df and Da camera directions, and one package will be mechanized on a goniometric arm to monitor the angular reflectance properties of the panels.

The HQE's are in a "trap" configuration. Here three silicon photodiodes are arranged in a package so that light reflected from one diode is directed to another diode. The output of each diode is summed, resulting in near 100% quantum efficiency. A single spectral filter per package is used, and four such packages provide coverage. at the four MISR wavelengths. One diode type will be used to obtain high quantum efficiency (QE) in the blue, and another type will be optimized for QE in the remaining three. bands. The diodes have been specified to have an internal quantum efficiency exceeding 0.995, to have a front surface loss of less than 20%, to have a linearity of response better than 99.99% over an *equivalent reflectance* range of 0.05 to 1.0, and to have SNR in excess of 500 at full scale.

The equivalent reflectance parameter is used to specify instrument signal-to-noise requirements. This parameter is defined as:

$$\rho_{eq} = \pi L_\lambda / E_{0\lambda} \qquad (2\text{-}1)$$

where L_λ is the spectral radiance incident at the sensor while observing a given target, and $E_{0\lambda}$ is the spectral exe-atmospheric solar irradiance at wavelength λ. (Both L_λ and $E_{0\lambda}$ are band weighted over the passband response.) To convert an equivalent reflectance into radiance, therefore, $L_\lambda = E_{0\lambda} * \rho_{eq} / \pi$ where $E_{0\lambda}$ is the exe-atmospheric solar irradiance, as given by the World Climate Research Programme (Wehrli, 1986).

Goniometer. The goniometer is a mechanized device which characterizes the relative diffuse panel radiance function with angle. It does so in a plane parallel to the spacecraft flight direction. A PIN package mounted to the goniometer arm swings through $\pm 60°$ to allow panel characterization appropriate to the along-track camera angles.

2.4 Data Modes

Global mode. There are several observational modes of the MISR instrument. Global Mode refers to continuous operation with no limitation on swath length. Global coverage in a particular spectral band of one camera is provided by operating the corresponding signal chain continuously in a selected resolution mode. In addition to the mode in which data from a particular channel are not averaged, the instrument provides the capability, selectable for each channel by ground command, of averaging four crosstrack by four along-track (4x4) samples, 2x2 samples, or 1x4 samples. Without this capability the data rate would be prohibitively high. Any choice of averaging modes among the nine cameras that is consistent with the instrument data rate allocation (3.8 Mbps averaged over an orbit; 9.0 M bps peak) is suitable for Global Mode. The nominal pixel averaging Global Mode envisioned for routine operations is given in Table 2-2.

Table 2-2. Nominal Global Mode

Camera	Spectral Band			
	Blue	Green	Red	Near IR
Df, Da	1x4	4x4	1x1	4x4
Cf, Ca	1x4	4x4	1x1	4x4
Bf, Ba	4x4	4x4	1x1	4x4
Af, Aa	4x4	4x4	1x1	4x4
An	1x1	1x1	1x1	1x1

Local Mode provides high resolution images in all four bands of all nine cameras for selected Earth targets. This is accomplished by inhibiting pixel avel aging in all bands of each of the cameras in sequence, one at a time, beginning with the first camera to acquire the target (Df) and ending with the last camera to view the target (Da), a sequence which takes seven minutes to complete.

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The instrument geometry limits the along-track length of 1 ocal Mode targets to about 300 km. This mode shall be used over the Mojave Desert, near Los Angeles, and White Sands, New Mexico, for instrument calibration purposes, as well as up to about 100 other sites selected for various scientific objectives.

In Calibration Mode the calibration photodiodes are activated and data from the cameras and photodiodes are acquired. During calibration the can ieras are ramped through a series of configurations which provide data through all integration times and data averaging modes, including the baseline Global Mode. Calibration Mode will be used on a monthly basis during routine mission operations, although early in the mission it will be used more frequently.

Engineering data. During flight the MISR instrument routinely transmits temperature measurements of the optical bench, optics, CCD, TEC, electronics, and photodiodes. These data are transmitted as part of the engineering data stream, both during routine science data acquisition, and during in-flight calibration activities. These data arc. used in conjunction with the pre-flight characterization data to provide the appropriate calibration coefficients, where temperature dependence is a factor. Other engineering data include an unlatch flag for the cover and diffusers, deploy or stowed flags for the diffuse panels and cover, motor currents, power supply current, and photodiode radiometry.

3. CAI,IBRATION REQUIREMENTS

In order to accomplish its scientific objectives, MISR is built to challenging performance specifications. Radiometric accuracy must be within $\pm 3\%$ (1 σ) over high reflectance, spatially uniform scenes, and polarization insensitivity is to be better than $\pm 1\%$. The instrument must be unaffected by image blur and scattering to better than 270 for a 5% equivalent reflectance (e.g., ocean) scene 24 pixels distance from a high-contrast edge (e.g., a cloud boundary). All performance requirements must be met through the first five years in-orbit. During the mission, data from the channels are sent to a ground processing center where they are radiometrically converted and co-registered to within ± 550 m along-track/ ± 275 m cross-track (2σ).

3.1 Spectral and radiometric specifications

The instrument design specifications have been defined in several internal controlling documents, including the Instrument Science Requirements and the instrument Functional and Design Requirements documents. Those specifications which drive the characterization plans for MISR are listed in this section. Spectral, radiometric, and stability specifications are given in Tables 3-1 to 3-4, respectively. All requirements are stated at the 10 confidence level.

Table 3-1. Spectral specifications.

Band	Center wav. (rim)	Cen. wav. uniformity (rim)	Know-ledge (rim)	Stability (rim)	Bandwidth (rim)	Bandwidth uniformity (rim)
1	443	± 1.0	± 0.5	± 1.0	25	± 2.0
2	555	± 1.0	± 0.5	± 1.0	15	± 2.0
3	670	± 1.5	± 0.5	± 1.0	15	± 2.0
4	865	± 2.0	± 0.5	± 1.0	25	± 2.0

In the above the center wavelength specification are tabulated in the cells bordered by the double lines; the bandwidth specifications by the bold lines. Knowledge and stability specifications are equal for both center wavelength and bandwidth parameters.

Out-of-band rejection. The system response is required to have an absolute transmittance in the rejection region of less than ().1%, at any wavelength, and average no more than 0.01%, over any 100 nm interval. The reje region is defined as all wavelengths shortward of $\lambda_{c,m}-2*\Delta\lambda_g$ plus all wavelengths longwa $\lambda_{c,m}+2*\Delta\lambda_g$ where $\lambda_{c,m}$ is the center wavelength (computed from a moments analysis), and $\Delta\lambda_g$ is the Gaussian full-width half-maximum (in-band best fit).

Table 3-2. Radiometric uncertainty specifications

ρ_{eq} (%)	Maximum radiometric uncertainty (%)
100	+3
5	±6
<5	Best possible

Between elements	ρ_{eq} (%)	Maximum relative uncertainty (%)
Pixel-to-pixel	100	±0.5
"	5	±1.0
Band-to-band	100	±1.0
"	5	±2.0
Camera-to-camera	100	±1.0
"	5	±2.0

Table 3-3. Temporal stability

ρ_{eq} (%)	Maximum annual change in response (%)
100 0 0 '	2
5	4

ρ_{eq} (%)	Maximum monthly change in response (%)
100	0.5
20	1.0
5	2.0

Table 3-4. MISR signal-to-noise ratio requirements

No pixel averaging (all bands)	
Equivalent reflectance	Minimum SNR
100%	700
70%	600
50%	450
20%	300
2%	100
< 2%	Best possible

4 x 4 pixel averaging		
Band	Equivalent reflectance	Minimum SNR
1	15%	250
	10%	225
2	7%	300
	4%	200
3	5%	325
	3%	200
4	4%	300
	2%	200

Modulation Transfer Function. The cameras shall have a modulation transfer function equal to or greater than 20% at 23.8 cycles/mm at all field points within the specified field of view.

Polarization. The peak-to-peak change in instrument response resulting from varying the plane of polarization, for a 100% linearly polarized stimulus, shall not exceed 2%.

Contrasting target. Two related forms of contrasting target requirements exist. The first describes the response required of a cloud/ ocean boundary type scene (a ρ_{eq}=100% half plane adjacent to a ρ_{eq}=5% half-plane). Here radiometry must free of instrumental adjacency effects within 24 pixels distance from the boundary. The second tax get type describes the response required of a lake/ surrounding land scene type (a ρ_{eq}=5% target 24x24 pixels in size surrounded by a ρ_{eq}=50% background). The center 8x8 pixels shall not be affected by the background.

3.2 Geometric specifications

Geolocation and registration. imagery from the nadir camera shall be geolocated with an uncertain y of *250 m in both cross-track and along-track directions. Further, imagery of a particular land surface target from the nine cameras shall be spatially co-registered with an uncertainty of ±275 m cross-track and ±550 m along-track (these are 2σ requirements). Because the 36 channels of image data are not intrinsicall y co-registered when acquired (see Figure 2-1), this co-registration must be achieved in the ground data processing, and is a prerequisite to the retrieval of geophysical parameters. MISR imagery shall also be projected to a high-altitude reference level situated 30-km above the surface. For these data, the registration uncertainty requirements are ±250 m cross-track and ±500 m along-track. The allowable land surface uncertainties are larger to enable attribution of a portion of the error budget to topographic relief errors.

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Pointing. Boresight angles Of the MISR cameras must be manufactured to tolerances within ±12 arcmin of nominal. In addition, pointing repeatability is to be achieved in-flightto*18 arcsec (3σ) in pitch, roll, and yaw over the temperature. range MISR will encounter in-orbit. The tight repeatability requirement, relative to the looser manufacture tolerance, is to insure that the image registration requirements are met with a minimum of ground data processing. Further, the MISR instrument stability shall be ±5 arcsec over 1 see, and ±8 arcsec over 420 sec (3σ) in pitch, roll, and yaw.

4. PREFLIGHT TESTING

Some degree of testing of MISR flight hardware is done at the component, camera, and system levels, as well as after shipment and integration onto the spacecraft. The. bulk the performance data, however, are collected at the camera level of assembly. By characterizing each camera individually, testing can be spread sequentially over tin ie and the test hardware is simplified. Camera testing is to be done using two MISR-dedicated thermal vacuum chambers. The camera-level approach to characterization also permits camera spares to be stored as calibrated, ready to fly hardware. The shorter system level tests are to be conducted in shared, more costly facilities. Radiometric stability is verified at the system level of assembly. Instrument geometric stability is characterized at the system level.

4.1 Component Testing

CCD. Each detector is screened for linearity, full-well, and dark current before assembly into an integrated focal plane package. Radiation testing, temperature. and humidity cycling, and other aging studies are conducted on each wafer, from which actual CCD arrays are manufactured.

Filter. Filter specifications are verified on the flight coating plates, before assembly into the final mosaic form. Testing at this phase includes spectral response, spatial uniformity of response, and out-of-band rejection. Thermal and moisture cycling, and radiation testing is conducted on flight-like assembly pieces. Structural integrity is verified visually under a microscope.

Lens. Lens field-of-view (FOV), effective focal length, distortion and lateral chromatic aberration, modulation transfer function (MTF), relative aperture and transmittance are verified before mating to a camera head,

4.2 Optical Characterization

The first of the MISR thermal-vacuum chambers is called the optical Characterization Chamber (OCC). This chamber is used to test a lens for MTF, back-focal length, and distortion. It is also used to test a given camera (lens and camera head) for MTF, focus, IFOV, stray-light, and extended target response. Inside is an optical bench, loaded with a collimator, target wheel, and gimbal to which the camera is mounted, The gimbal is used to swing the camera such that it can view the source at any field position. The target wheel contains a number of pinhole sources for point-spread function mapping, as well as several extended targets. Illumination is provided by an external xenon source, with fiber optic feed. Testing proceeds in an automated fashion, with computer control of the gimbal. As the chamber has no windows, testing can be conducted independent of other clean-room activities. The "ground support electronics (GSE)" computer is used to acquire camera video and engineering data.

4.3 Spectral Calibration

The second MISR thermal vacuum chamber is termed the Radiometric Characterization Chamber (RCC). In this chamber the spectral, radiometric, and polarization studies are conducted. As the illumination sources for this chamber are external and transmitted through a large chamber window, provision must be made to isolate RCC tests from other clean-room activities. A 2.4x 4.9 m (8 x 16') tent, made of black plastic ("Fraloc"), envelopes the RCC test equipment and chamber window to provide the necessary light shielding.

The first test to be conducted on a given camera within the RCC is spectral calibration, Data collected by the calibration team will be used to determine:

- equivalent square-band representation, including the central wavelength of each pixel (as well as the array average), including the out-of-band response;
- best-fit gaussian representation, including the full-width at half maximum (FWHM) response of each pixel and array average for the in-band region; and

- out-of-band suppression.

These data will describe the system, and include the effects of the optics, filter, and detector response with wavelength.

For this test use will be made of a monochromatic source, recording the relative camera output as a function of wavelength. The camera under test will be placed within the RCC and view a Spectralon diffuse panel illuminated with light emerging from the exit slit of a monochromator. (The Spectralon panel and monochromator are external to the chamber). In this configuration a greater area of the focal plane can be illuminated than if the monochromator is viewed direct] y. The slit is wide enough to illuminate all four bands simultaneously. The monochromator will scan from 400 nm to 1200 nm with a step size of 0.5 nm. The monochromator output spectral density is calibrated using unfiltered laboratory photodiode standards. A number of standards are used, which when combined monitor the source with a spectral 1 y flat (or known) detector response.

Spectral calibration of the monochromator is also required periodically. Here the monochromator grating position versus output wavelength is determined. This is done by replacing the xenon lamp, used during camera test, with a mercury vapor lamp. The latter source has known spectral lines. This calibration will be repeated as needed to insure knowledge of the monochromator output to 0.25 nm.

4.4 Radiometric Calibration

During radiometric calibration the relationship between an incident radiance field and camera digital output is established. This is done using an "ideal" target which emits or reflects unpolarized light, is uniform in space and angle, and lacks spectral features such as absorption lines. Through knowledge of this source exitance the calibration equation can be established for a sensor:

$$L_\lambda = G (D - DO) . \tag{4-1}$$

Here, L_λ is the incoming spectral radiance at band center, D is the sensor digital number output, G is the detector gain coefficient, and DO is the offset digital number coefficient.

The accuracy with which this can be accomplished will determine the lower bound for uncertainty in radiance measured while viewing an Earth scene. This uncertainty, however, will be applicable to a majority of scene types. The degradation in radiometric accuracy experienced while viewing a complex scene type is quantified through the camera polarization, contrasting-target response, stray-light rejection, and near-saturation characterizations.

During camera calibration, data are gathered through the sensor's dynamic range. For camera tests these data are used directly with the calibration equation. When the system electronics are included in the signal chain, however, the camera 14 bit linearly encoded output data are square-root encoded to 12 bits through used of a look-up table stored in a PROM. The data must therefore be linearized by squaring before fitting to the calibration equation. During pre-flight calibration the majority of data will be taken without use of the system electronics. Consistency in calibration between the approaches will be verified.

Those specifications which require the radiometric calibration of the cameras using an "ideal" target are discussed in this section. These specifications apply to a scene type which is uniform and unpolarized, During test, such a scene is simulated using an integrating sphere. With the sphere the following objectives can be accomplished:

- measurement of signal-to-noise ratios and through a range of incoming radiances;
- determination of the gain and offset coefficients for each pixel;
- estimation of calibration uncertainties at the 10 confidence level;
- verification of shielded pixel measure of baseline subtraction (BLS) and dark current;
- verification of linear calibration equation or development of higher order equation, as needed;
- determination of the calibration coefficient temperature dependence;
- characterization of camera response as a function of scene history (previous level of illumination); and
- comparison of measured system response to mathematical model.

Figure 4-1 depicts the test set-up during camera calibration, The aperture of the integrating sphere will overfill the field-of-view of each camera, independent of camera design. This simulates the Earth-view geometry and allows inclusion of stray and scattered light sources. The sphere is 1.6 m (65") in diameter, has a 76x23 cm (30x9") exit port, and has a 30 cm (1 2") external sphere with variable aperture. The sphere will be sequenced through a number of lamp-on settings, allowing digital data to be collected at ten radiometric levels. At least three repetitions of data will be collected at any one radiometric setting. The coefficients in the calibration equation will be determined for each pixel using these data. A statistical approach called the Fidelity Analysis (Chrien, et al., 1993) will be used to fit a straight-line through the data and provide a measure of the uncertainty in this fit. The Fidelity Analysis approach is preferred to conventional least-squares approach in that this uncertainty can be determined even at radiance levels not represented by the test. Other calibrations will be performed by varying the sphere from maximum to minimum and returned to a maximum radiance output setting, thus verifying calibration is independent of scene history. Radiometric calibrations will be performed at the CCD operating temperature, with

system electronics placed in their minimum, nominal, and maximum operating temperatures (- 10°, 10° and 40° C), and at two different integration times.
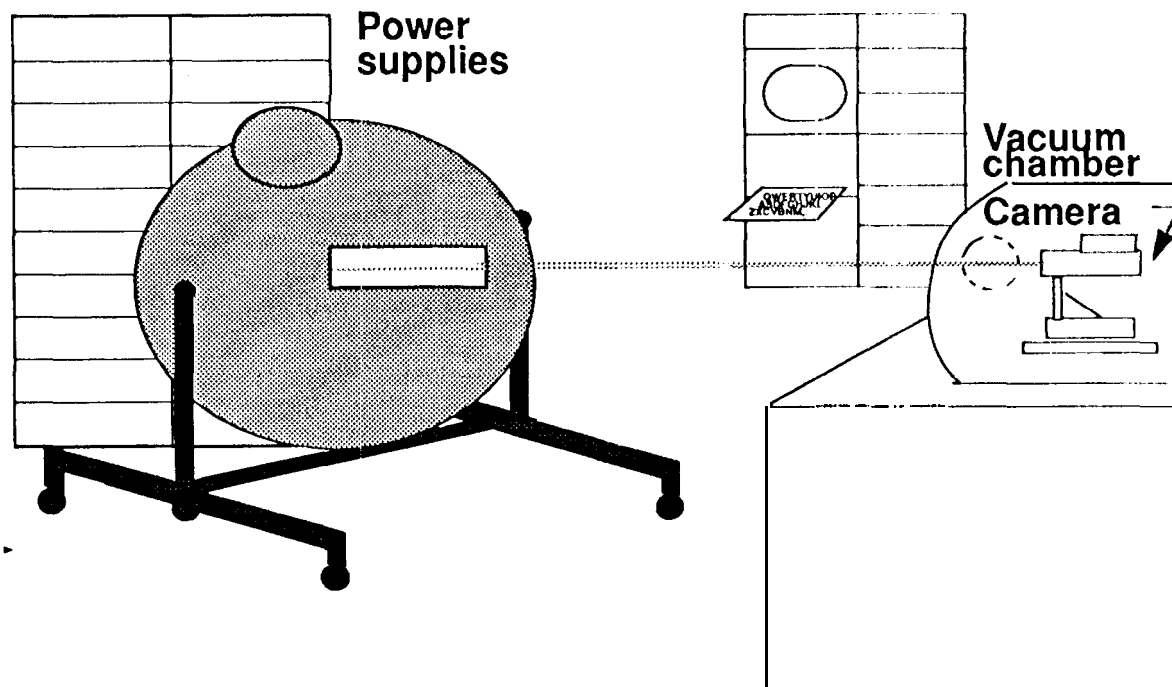

Figure 4-1. **Radiometric** calibration set-up.

Radiometric traceability. The integrating sphere output will be calibrated using the laboratory diode standards and laboratory MISR filters. These components will be placed in the thermal vacuum chamber and view the sphere through the window. During this time the chamber will not be under vacuum, and the camera will not be present inside the chamber. Following this source characterization the diode standards will be removed, the camera inserted into the chamber, and the chamber vacuum pumped for calibration. The integrating sphere incorporates a photodiode stability monitor which will provide a measure of sphere stability over the course of radiometric calibration. Radiometry is verified through round-robin intercomparisons with other EOS instrument teams, as well as with NIST. For the round-robins stable detector standards, provided by the National Research Laboratory of Metrology (NRLM) of Japan, and the Optical Sciences Center, Tucson, are utilized to view the various instrument sources in turn.

4.5 System Tests

After camera characterization the cameras are mounted onto the MISR optical bench, along with the OBC elements. The optical bench is attached to the Primary Support Structure along with the electronics and radiators to complete the instrument. At this level thermal, vibration, and camera pointing studies are conducted, Although radiometric calibration is not repeated at the instrument level, stability is verified.

Radiometric Stability. The test equipment used to verify radiometric stability is the MISR Aliveness and Stability Test (MAST) tool, The MAST is a light fixture external to the MISR enclosure. It illuminates the deployed diffuse panels, thus providing a full-field illumination of

each camera's FOV. It consists of a 1000 W xenon lamp, with a fiber-optic feed. The far end of the fiber bundle is attached to the instrument, clearing all glint baffle structures, There are two fiber bundles, one to illuminate each panel in turn. As the fiber has a vacuum feed, data can be acquired at ambient or vacuum pressures. Ambient pressure, room temperature data will be the baseline test condition. These tests will be conducted before and after instrument vacuum testing, post-ship of the instrument to the spacecraft integrator, and at the observatory level to verify that there is no instrument cross-talk. (If possible data will also be acquired at the Vandenberg launch hanger).

Pointing. At the system level the pointing angles and their stability will be verified using the Collimator Array Tool (CAT). This tool consist.. of a set of nine collimators which are precision mounted into a fixture at the nominal MISR camera boresight angles. This fixture is then mounted to the MISR instrument such that one CAT collimator corresponds to each MISR camera. MISR and the CAT will then be placed in a thermal-vacuum chamber. Each collimator will then project the image of a precision-made chevron target into its corresponding MISR camera. This target is shown in Figure 4-2. The image created on each MISR CCD will undergo centroid analysis to ascertain the boresight of the MISR cameras with respect to the CAT. Chevron CCD images will be collected as MISR is thermally cycled over the temperature range expected in-orbit.
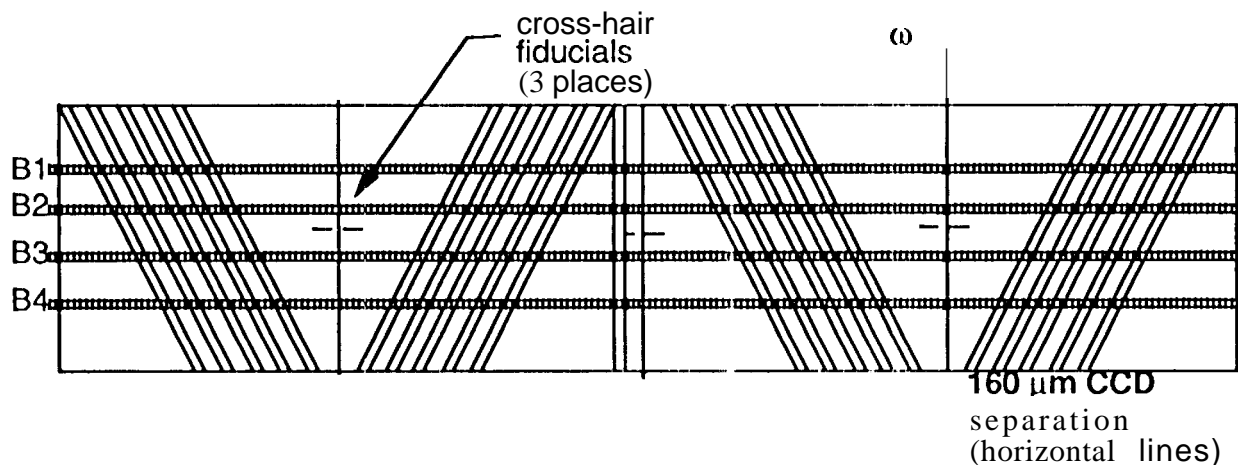

Figure 4-2. CAT chevron test target used to establish relative camera pointing directions.

Diffuse Danel uniformity of illumination. Verification of the uniformity of panel illumination will be done by using the integrating sphere as a uniform source. However, to achieve a more collimated output, the aperture will be cut to 2.5 x 51 cm (1 x 20") and the operating distance will be increased to 7.3 m (24 ft). This will produce rays that are "collimated" to within approximately 4° across the length of the calibration target, The increased operating distance reduces the sphere's output by about a factor of 36, but the IR channel will be remain responsive since the sphere has a strong radiant output in the IR, as compared to a solar source. The non-uniformity measured with this configuration will be compared to the non-uniformity measured during camera calibration. Any differences in uniformity will be due to back reflections and scattering of light onto the calibration targets.

5. IN-FLIGHT CHARACTERIZATION

Ml SR makes use of multiple sources of calibration data. The preflight test plans and OBC system were described previously. Other sources of calibration data include overflight calibration campaigns. These data will be combined to determine the uncertainty in sensor calibration.

5.1 overflight calibration

After MISR is launched the radiometric calibrations established by the preflight and OBC analysis activities will be supplemented with an overflight calibration program. Here in-situ surface bidirectional reflectance factor data are collected and an atmospheric characterization is made over a region to be viewed by MISR in a high-resolution data mode (Local Mode viewing). With use of a radiative transfer code the radiance impinging on MISR is computed. This establishes an accurate calibration, particular y for the nad ir camera.

5.2 Use of multiple calibration data sets

Use will be made of all data sets to provide the coefficients needed to describe the radiometric response of the instrument. It is required that data products be produced using timely data which reflect the current response function for the instrument. It is also required that there be no discontinuities in data products that area result of abrupt changes in these calibration coefficients due to finite sampling and precision of the techniques. For this reason MISR will apply a smoothing function to the monthly calibration data sets. After the data are fit to a low-order polynomial curve, the calibration coefficients provided by the data fit are compiled. It is likely that this fit will be re-established each month, using the last ten (or so) measurement sets. Thus, after each new in-flight calibration activity using the OBC, a new set of coefficients will be computed. It is believed that each new coefficient set will vary only slightly from the previous. It is recalled that the instrument is being built to a stability specification of 0.5% limit on response change per month, and 2% change limit per year.

Radiometric verifications to the calibration are enabled by comparing with the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) radiance pi oducts over common viewing locations, as well as using MODIS and ASTER derived radiance data from their respective field operations. MODIS and ASTER fly on the same spacecraft as MISR.

5.3 Science Computing Facility (SCF) image analysis

In-flight performance assessment of the MISR instrument will be conducted at the MISR Science Computer Facility. Here noise and dead pixel assessment will be conducted, trend analysis performed with the flight engineering data, relative calibration provided using scene studies, and the absolute radiometric coefficients determined from the multiple data sets. Radiometric uncertainty will be reported for both ideal targets (such as the calibration sites), and representative scene sites. The routine Local Mode data will be invaluable for these studies.

6. DATA PRODUCTS

6.1 Reformatted annotated product

Square-root encoding is performed in-flight in order to compress MISR data and prepare for transmission. Thus, the 14-bit data which are produced by an individual camera are square-root

encoded, through use of a table look-up process, and reduced to 12-bit numbers. At the lowest archive level for MISR data, Level 1A, this step is reversed, then padded to a 16-bit word. That is, the Level 1A data are representative of the original camera output in which the digital number (DN) values depend linearly on the input radiance. In addition to these camera DN values, the Level 1A product is appended with platform navigation, MISR engineering parameters, and associated calibration coefficients, as shown in Table 6-1.

Table 6-1. Level 1A product

Product	Principal contents
Level 1A: Reformatted Annotated Product	• Data numbers linearized via square-root decoding • Navigation, engineering, and calibration data

6.2 Radiometric product

The Level 1A data are used as input to the Level 1B processing code. The primary objective of the MISR Level 1B1 processing algorithm is to produce MISR band-averaged radiances from the camera digital numbers (DN). The Level 1B1 product also contains a clear-sky mask for each camera. These parameters are summarized in Table 6-2. The radiometric data are reported at the same spatial resolution as the input DN, and no re-sampling is performed, Processing is done routinely on all transmitted MISR data.

Table 6-2. Level 1B1 Radiometric Product

Parameter name	Units	Horizontal Sampling (Coverage)	Comments
Radiance	$W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$	250 m nadir, 27S m off-nadir, or averages pert} camera configuration (Global)	• Radiometrically-scaled data • No geometric resampling • 9 cameras, 4 bands • Uncertainty reported in Ancillary Radiometric Product
Clear-sky mask	none	1.1 km (Global)	Values 1 (clear enough), O (unclassified)

The algorithm used to produce the Level 1B1 Radiometric Product requires knowledge of the radiometric calibration coefficients for each pixel. This instrument calibration is updated monthly with use of On-Board Calibrator (OBC) data, and semi-annually during field campaigns (FC). The coefficients used in the Radiometric Product generation are documented in the Ancillary Radiometric Product (ARP), summarized in Table 6-3. Also included in the ARP is radiance uncertainty, spectral and instantaneous field-of-view (IFOV) information. The ARP is generated

at the MISR Science Computing Facility (SCF), updated as needed, and delivered to the DAAC. Thus, production of the ARP is not part of the routine DAAC processing of MISR data.

Table 6-3. Level 1B1 Ancillary Radiometric Product

Parameter name	Units	Comments
Date range	none	• Revision number • Date/ time range of applicability
Radiometric calibration coeffi-cients	W m^{-2} μm^{-1} sr^{-1} DN^{-1} (gain); DN (offset)	• 1S04 pixel values for both gain and offset for 9 cameras and 4 bands and at several temperatures
Camera calibration uncertainty	%	• 1504 pixel values for 9 cameras, 4 bands at 5 radiometric values
Dead pixel mask	none	• Values 1 (responsive), O (dead pixel)
Spectral band param-eters (center wave-length, bandwidth, transmittance)	nm	•Equivalent square-band and gaussian representation provided
Instantaneous field-of-view (IFOV)	arcsec	• Crosstrack and along track half-power points of pixel responsivity function with angle
Clear-sky coeffi-cients and thresholds	none	● Updated as algorithm matures
Exo-atmospheric spectral solar irradi-ances	W m^{-2} μm^{-1}	• Weighted over each MISR spectral band

At a minimum radiance conversion will be implemented through a simple radiance scaling algorithm in which a gain and offset coefficient (specific to each pixel) are used in conjunction with a linear calibration equation. During preflight characterization the need to incorporate instrument correction terms will be determined, Contrast enhancement through point-spread function (PSF) deconvolution, out-of-band response removal, and pixel nonuniformity corrections are to be considered, The need for these corrections is dependent on instrument performance, which is currently uncer evalutaion.

6.3 Registered Imagery

Following radiornetric conversion, MISR images are geolocated and co-registered (angle-to-angle and band-to-band) to produce the Level 1 B? Gee-rectified Radiance Product, Preparation for this processing begins at the SCF, where a set of reference orbits (233 orbits at nine view angles) are constructed from initially acquired, cloud-free, MISR scenes. These. reference images are geo-located using ground control points. Subsequent MISR imagery ate matched to the reference MISR data sets, with like view-angles compared. Spacecraft-supplied navigation is used to provide a first

guess at image geolocation for newly acquired data, and matchng is performed as required, Thus the approach is adaptive to the platform attitude knowledge performance. The geometric camera model is obtained from the preflight testing program, and refined once in orbit using actual MISR imagery. The Gee-rectified Radiance Product, Ancillary Gee-Rectified Product, and Geometric Calibration Dataset contents are summarized in Table 6-4.

Table 6-4. Level 1B2 products

Product	Principal contents
Level 1B2: Gee-Rectified Radiance Product	• Resampled radiances projected onto Space Oblique Mercator grid (at surface and 30 km above sea level) • Projected clear-sky mask • View and illumination geometric parameters
Ancillary Gee-Rectified Product	• Latitude and longitude of SOM grid points • Surface elevation and slope data • Surface classification data
Geometric Calibration Dataset	• Mapping transformations from image space to Earth reference • MISR images acquired early in mission to which later data are registered • Parameters describing camera orientation, pixel view directions • Ground control points

6.4 Science products

Level 2 products use these radiances to produce geophysical measurements of aerosols, surface hi-directional reflectance factors and cloud parameters. The at-launch standard data products which are to be routinely generated at the NASA Langley Distributed Active Archive Center (DAAC) are summarized in Table 6-5. More information on these products is available within the MISR project documents, such as the . MISR Data Product Description (DPD) document, These are listed in the reference section, and are available on the World Wide Web (http://www-misr.jpl.nasa.gov). In addition to the routinely generated standard products, there are a number of

ancillary data products and datasets that are generated at the MISR SCF and archived at the DAAC. These aid in the production or interpretation of the standard data products.

'I'able 6-5. Level 2 products

Product	Principal contents
Level 2: Top-of-atmosphere (TOA)/ Cloud Product	• Top-of-atmosphere (TOA) bidirectional reflectance factor (BRF) • TOA albedo at reflecting-level reference altitude (RLRA) and at a 30 km reference altitude • Reflecting-level classifiers, including elevation • Cloud masks (thick and high clouds)
Level 2: Aerosol/ Surface Product	• Tropospheric aerosol optical depths and composi- tional model identifiers • Surface hemispherical- dire. tional reflectance factor (HDRF) • Surface bi-hemispherical reflectance (BHR) • Ancillary meteorological and atmospheric data

7. SUMMARY

MISR has recently completed a Critical Design Review. Much of the test equipment needed to characterize both the engineering model and flight units has been procured. Testing of the engineering model will confirm the approaches described here and allow the team to gain experience with handling the large data volumes of data to be produced by the MISR instrument. After these procedures and data reduction approaches have been refined, the team will begin characterization and calibration of the flight hardware,

Acknowledgments

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